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Preliminary design and numerical analysis of a scrap tires pyrolysis system

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Abstract

A plant prototype for whole scrap tires disposal and the consequent syngas production via pyrolysis has been developed. A numerical analysis on the innovative pyrolysis reactor, constituted by an autoclave closing device and an explosion-proof water system has been carried out. The aim of this analysis is to investigate the fluid-dynamics in the pyrolysis chamber and model the syngas production. The simulations, performed in the pre-realization system phase, have allowed to determine: i) the flow field of the fluid within the reactor, so as to optimize the geometry (e.g. size, vacuum system, water tank); ii) the temperature range, in order to determine the correct placement of thermocouples within reactor and prevent overheating that could compromise the safety of the system; iii) the pressure range, necessary to avoid the eventual flooding of the tires themselves. Thanks to these results, the test bench has been built at the CURTI S.p.A laboratory and experimental analysis has been performed. The experimental data are acquired and then elaborated, as shown in the paper.

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Keywords: Pyrolysis; syngas; scrap tires disposal;

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1. Introduction

The problem of scrap tires disposal is taking increasingly worrying dimensions, especially in the Western world. In fact, Europe produces annually about 2.5 million tons of tires to be disposed of, while Italy produces 300,000 tons. In America, the problem is even worse, to the point that it has induced neighboring states to approve laws that regulate the exodus of these bulky residues from one state to another. To date, the techniques for scrap tires disposal differ in type and related problems, among which there are [1]: i) landfill disposal, e.g. huge volumes occupied and long residence times without biodegradability, aggravated by the fact that new species of insects, extremely harmful to humans often nest in the scrap tires.; ii) grinding and crushing, which, although yielding a partly reusable final product, unfortunately have an extremely high cost in terms of mechanical energy required for the process and carbon dioxide (CO_2) emissions; iii) incineration, whose environmental impact is significantly negative; iv) the use as secondary fuel in cement kilns, in addition to being harmful in terms of pollutant emissions, also needs a mechanical pre-treatment very expensive and energy-intensive and does not offer the recovery of the metal part of the tires. v) tire pyrolysis, i.e. the slow heating in the absence of oxygen, which leads to the production of gaseous compounds (syngas), liquids (oils) and solids (char) plus the separation of the steel; also all pyrolytic products are reusable. Pyrolysis, Gasification, and Liquefaction (PGL) are in fact three related technologies that can potentially recover useful resources (i.e., energy, chemical raw materials, steel and fiber) from waste tires [1]. However, despite a multitude of announcements over the years, only very few plants seem viable in the world today. Other studies (see for example [2,3]) confirm the applicability of the syngas as an efficient fuel for various energy systems.

This paper shows a fluid dynamics simulation study carried out to support the building of an experimental test bench for the pyrolysis of whole scrap tires, with the final goal of creating a continuous industrial plant for tires disposal and simultaneous syngas production.

2. Description of the tires pyrolysis system test bench

The waste tires pyrolysis test bench built by CURTI S.p.A. at the Faenza laboratory, consists of six key components (Fig. 1): a pyrolysis reactor (A), a condenser (B, C), a filter for the syngas (D), a centrifugal fan (E), a Bunsen burners array (F), and a chimney hood (G). Figure 1 shows the layout of the experimental plant. The syngas tube (orange line), the water intake tube (blue line) and the water discharge tube (green line) are indicated.

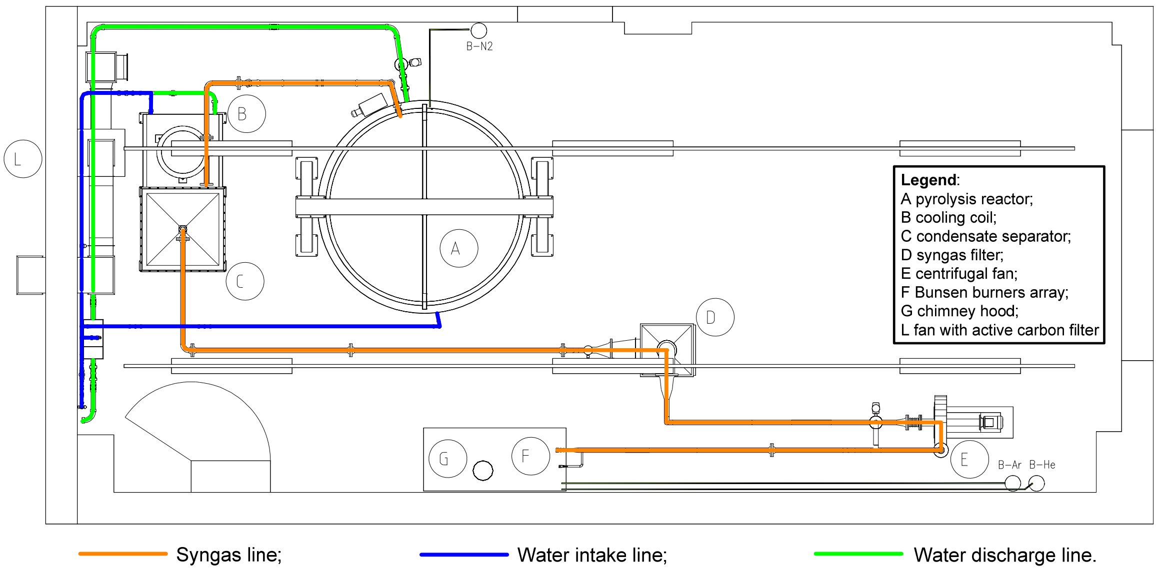

Fig. 1. Pyrolysis test bench: layout.

Scrap tires are pyrolysed within the reactor (Fig. 1, A); the gases produced (syngas) are extracted from the reactor through a hood and they are introduced into a condenser. This consists of a cooling coil (B) followed by a condensate separator (C), in which the condensed liquid fraction is discharged through a steam trap, while the gaseous fraction is sent to an in-house developed and patented filter (D). From here, through a centrifugal fan (E), the syngas is delivered to a Bunsen burners array (F) with a pilot flame, in which it is burned. The fumes thus produced are evacuated through a hood with organic filters (G), in order to reduce pollutants emission. The test bench is also equipped with a fan (L) for the extraction of potential gas leaks in the laboratory.

The pyrolysis reactor has a cylindrical shape and it consists of two main parts: the base, called "tank", and the cover, called "bell". The innovative patented feature of the reactor is the autoclave closing. In fact, the chamber is closed by placing the "bell" on to the cylindrical tank containing water below, necessary to ensure the safety of the system (explosion-proof water system). Since the bell diameter is less than the tank's, the water free surface, external to the bell itself, remains also in direct contact with the external environment. Inside the reactor, the pyrolysis products extraction system and the platform (or "banquet") on which the tires pyrolyse are found. The platform is equipped with a central pivot directly immersed in the water in the tank below. To limit the amount of water that evaporates during the pyrolysis process, a steel cylindrical element ("inner tube") is placed around the platform pivot, on the water surface, and on it is a porous medium of toroidal shape (named simply "o-ring") made by CURTI. This solution still ensures autoclave closing of the reactor despite small differences in diameter both near the pivot of the banquet and near the sidewalls of the chamber. To maintain the water level and avoid flooding of the tires, the water in the tank is continuously fed and discharged through suitable tubes (Fig. 1, blue and green line, respectively). In addition, a nitrogen tank (B-N2 in Fig.1) is connected to the reactor so that flushing between two pyrolysis experiments can clean it.

Externally, in the circumferential direction, the pyrolysis chamber is divided into sectors containing resistors , with unitary voltage of 400 V and power of 2100 W each, necessary to bring the chamber to pyrolysis temperature. To limit the heat exchange between the water in the tank and the resistors, and to also avoid water boiling, all the resistors have been suitably well-insulated.

To perform the experiment, whole scrap tires are placed on the platform in the centre of the open chamber. Then, the reactor is closed positioning the bell on the tank by means of a winch. Lateral resistors bring the system to a suitable temperature (estimated to be about 500 °C [4-7]) in order to kick-start the pyrolysis process. At the same time, the evacuation system of the gas products is activated. The solid products (e.g. char, metal residuals) and the oil are collected in a tray at the base of the platform, while the gas products are extracted through a hood positioned centrally above the tires themselves.

Then, gases are evacuated through a circular output section, built directly on the sidewall of the chamber. The suction pressure is obtained by a side channel blower able to ensure proper sealing.

3. Design and optimization of the pyrolysis reactor

The experimental test bench has been built with support of numerical analysis, performed with a commercial code (ANSYS Fluent 6.3), on a theoretical model of the pyrolysis reactor. In particular, the pyrolysis process into the reactor has been investigated, starting from a preliminary configuration of the chamber (first geometry - Fig. 2). Thermo-fluid-dynamic simulations were conducted to obtain information on:

- the flow field followed by the fluid (pyrolysis gas products) within the chamber, in order to highlight the presence of any stagnation points and vortices so as to optimize the geometry of the reactor (chamber size, type and positioning of the vacuum system);
- the temperature distribution inside the reactor in order to determine the placement of thermocouples and avoid any overheating compromising the safety of the whole system;
- the pressure distribution in the reactor, in order to evaluate the displacement of the water surface in the tank, base of the chamber, and eventually make changes to the tank and to the banquet supporting the tires.

The preliminary geometry of the pyrolysis reactor is shown in Figure 2. In this first configuration, the platform for the waste tires support has four legs fixed at the base of the tank, in which the condenser coil and also the ends of the resistors are immersed. This layout involves rather large tank size. Hence, an analysis on the fluid-dynamic conditions inside the reactor has been conducted to assess the most efficient positioning of the internal components.

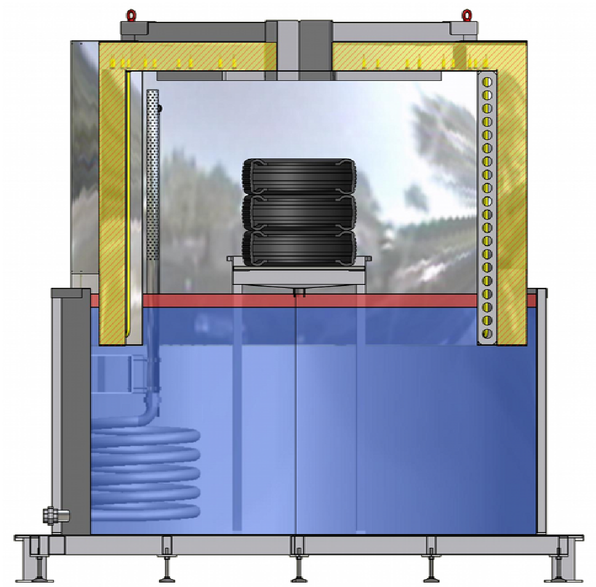

Fig.2. Pyrolysis reactor: first geometry.

3.1. Syngas extraction system: shape and position

In this section the investigation on the extraction system of the syngas is reported. At first, the displacement of this system has been analyzed: lateral position (Fig. 2) and central position within the reactor were considered.
In the first geometry (Fig. 2), the vacuum system is a single collector placed in the peripheral zone of the chamber. Using ducts flow field governing equations, it is immediately observed that the placement of a single sensor in this area, within a cylindrical domain, would give rise to strong pressure gradients and thus to non-homogeneous flow field also aggravated by the rather slow pyrolysis process. Moreover, there is no guarantee that the totality of gas products (syngas) is extracted. To avoid these problems, it was necessary to place the extraction system in a central position.
Then, the vacuum system shape has been investigated. Two typologies are considered: a tubular collector and a hood.
The analyzed collector (Figs 2, 3(a)) has a cylindrical shape with a diameter of 3" and it has holes along its entire surface; the output section of the syngas is at the end of the cooling coil on the side wall of the tank.
The hood (Fig. 3(b)), instead, is placed at the top within the reactor, with the syngas outlet section placed high up on the sidewall of the bell.
In both cases, connected to the collector (or to the hood), there is a 100 Nm^3/h fan (radial blade, backward), in turn linked to an inverter. The fan is capable of realizing a vacuum equal to 2000 Pa.
To assess the most efficient extraction system, an analysis on the fluid-dynamic conditions inside the reactor has been carried out.

3.2. Numerical analysis

Numerical analysis was conducted assuming as geometric domain the inner part of the reactor, between the free surface of the water contained in the tank and the upper surface of the bell.
Varying the shape of the extraction system, located in the centre of the chamber, two different meshes are realized: one with the collector (Fig. 3(a)) and one with the hood (Fig. 3(b)). The meshes, realized with a commercial program (Gambit 2.4.6), consist of about 464000 hexahedral and tetrahedral cells.

a) b)

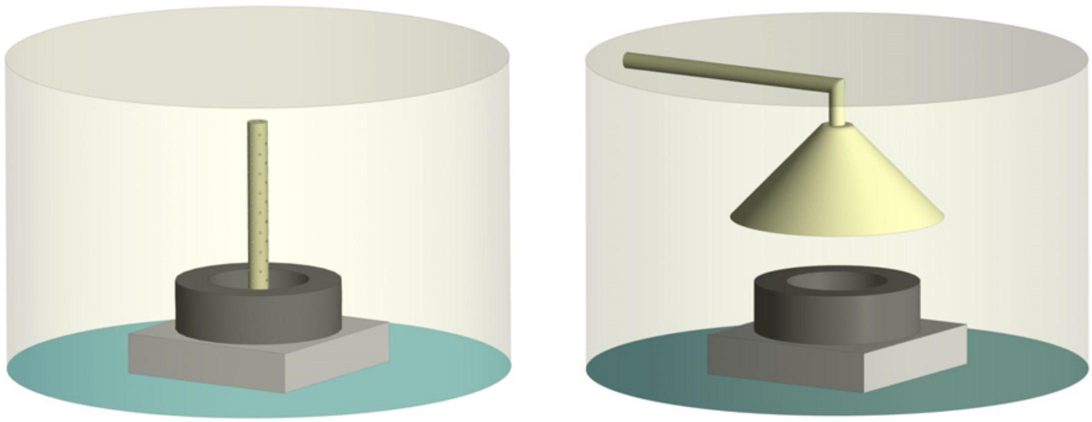

Fig. 3. Geometrical domain: (a) reactor with collector; (b) reactor with hood.

Fluid-dynamic simulations were performed assuming operation in steady state conditions. The k-ε turbulent model has been activated. Common-boundary conditions are assumed:

- it is assumed only one tire is in the reactor. This is a solid with cylindrical shape, hollow inside; its external surface is set as a source generating syngas;
- the output section of the collector (the output section of the pipe of the hood) coincides with the section through which the syngas exits the chamber. This section is characterized by a pressure of -2000 Pa;
- the upper wall of the pyrolysis chamber is considered adiabatic;
- the water free surface in the tank below is assumed to be at a temperature of 100 °C and is modelled as a water steam generator;
- the sidewall of the chamber was considered at a constant temperature (T = 500 ° C [3-5]).

3.3. Pyrolysis process modeling

To model the rather complex pyrolysis process, the following assumptions were made [3-5]:

- the pyrolysis process occurs at a temperature of 500 °C;
- the pyrolysis of a generic new car tire results in 70% of the weight of the tire to turn into syngas;
- the pyrolysis process duration of a new car tire, is 2.5 hours and 50% of the organic part pyrolyses in the first 10 minutes.

Figure 4 shows the trend of the estimated syngas mass flow versus time. In the first analysis, this trend was assumed linear in time.

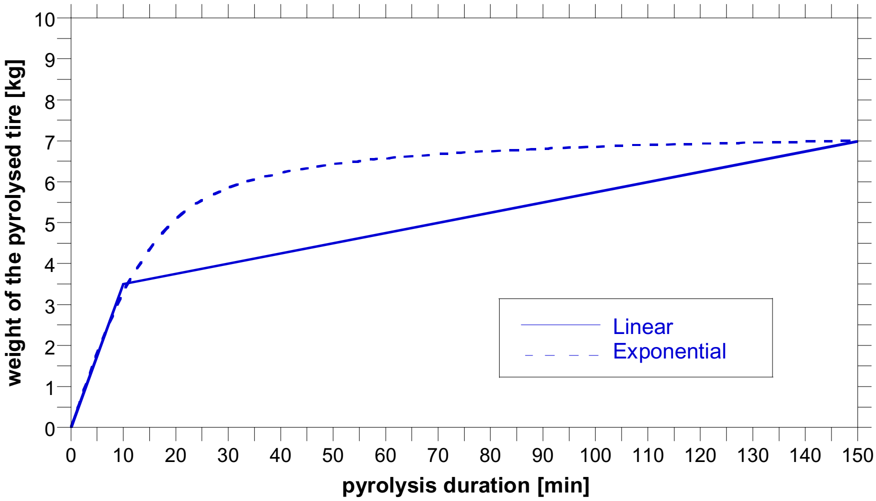

Fig. 4. Estimated syngas mass flow.

The considered composition (chemical species) of the syngas by commercial tires pyrolysis is reported in Table 1, according to [8]. Using these data, mass and volume fractions and molecular weight of the syngas produced by the pyrolysis of a single new tire have been calculated.

Table 1. Estimated average composition of syngas produced by pyrolysis of a single new tire.

Chemical species		Mass fraction [%]	Volume fraction [%]
	g/h	X_i [%]	Y_i [%]
H_2S	3,2	3,35	0,775
H_2	19,6	20,50	80,667
O_2	0,4	0,42	0,103
CO	4,0	4,20	1,176
CO_2	8,4	8,79	1,571
CH_4	8,8	9,19	4,527
CH_3-CH3	6,8	7,10	1,867
CH_2-CH_2	6,4	6,70	1,881
C_3^+ (C_3H_6)	38,0	39,75	7,433
Tot. g/h	95,6	100,00	100,00
Syngas molecular weight		7,8692	

3.4. Results

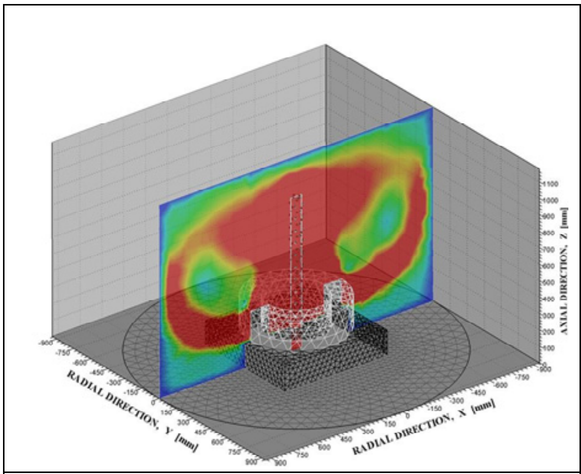

Fig. 5. Mesh with collector: velocity magnitude - (normal. values)

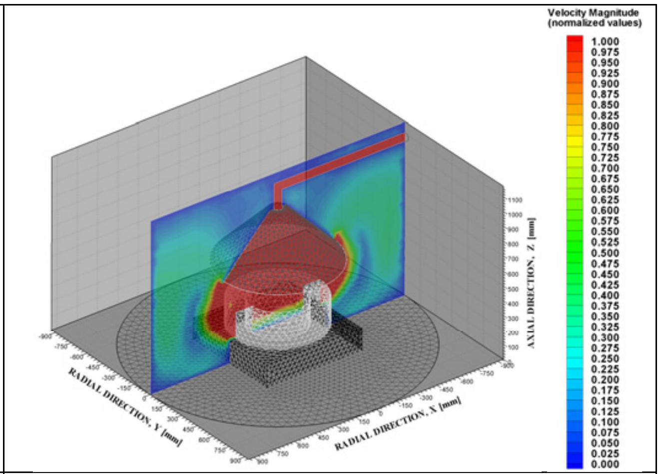

Fig. 8. Mesh with hood: velocity magnitude - (normalized values)

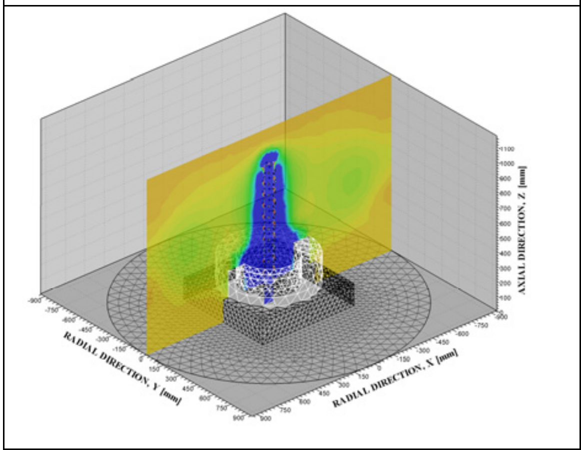

Fig. 6. Mesh with collector: static pressure - (normalized values)

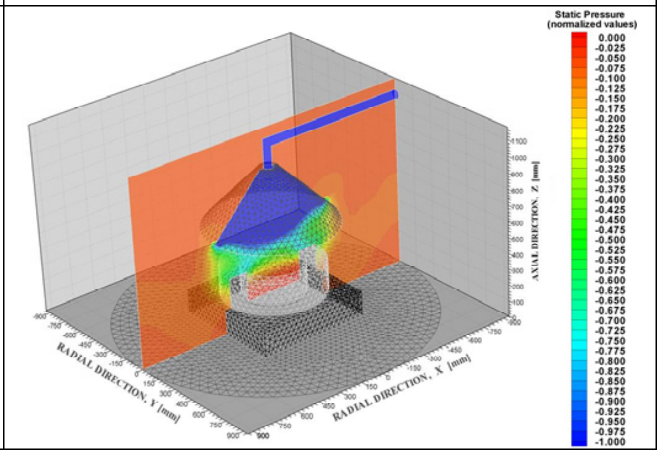

Fig. 9. Mesh with hood: static pressure - (normalized values)

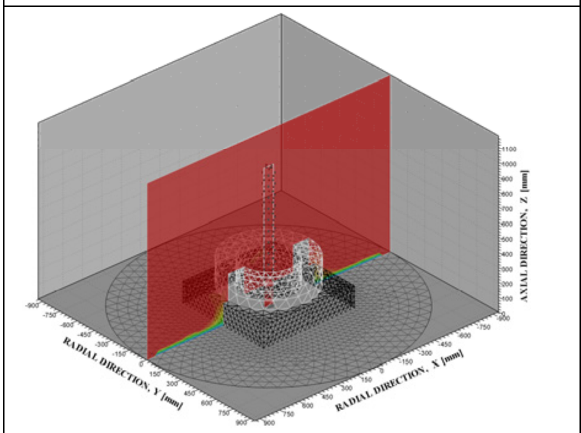

Fig. 7. Mesh with collector: temperature [K]

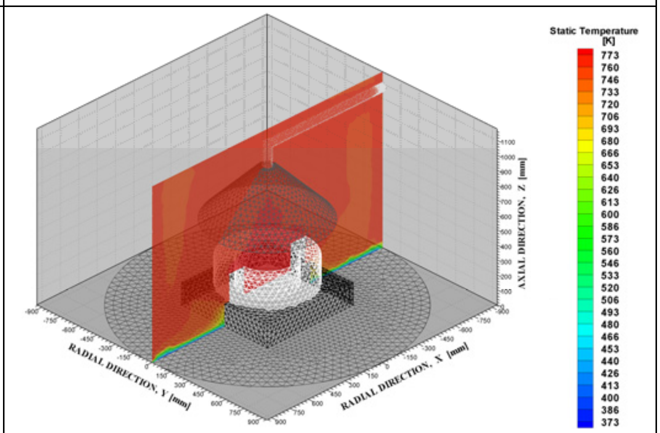

Fig. 10. Mesh with hood: temperature [K]

The assumption of a collector (Fig. 3(a)) offers almost symmetrical flow field of the gas produced (Fig. 5), characterized by rather uniform speed values throughout the domain. A recirculation is noted in the central area of the reactor, where the maximum speed values are obtained. Also the temperature range presents a symmetrical and uniform distribution throughout the domain (Fig. 7), showing a thermal gradient near the water free surface, where the heat exchange between the syngas and the liquid takes place. The central vacuum is such that it ensures a symmetrical but non-homogeneous pressure field (Fig. 6): the minimum pressure values are reached at the holes of the sensor itself, while in the central area and near the sidewalls localized pressure gradients are deduced; these may give rise not only to strong variations in physical properties of the fluid, but also to not complete extraction of the entire syngas mass produced. These results point to an excessive size of the chamber, highlighting also the need to use a single wide intake section not divided into small holes.
Furthermore, the positioning of the syngas outlet from the pyrolysis chamber and the size of the tank containing water have been analyzed. In fact, observing the geometry with tubular sensor (Fig. 3 (a)), the syngas output section is positioned on the basis of the chamber. Precisely, the syngas is sucked from the collector at the centre of the reactor and it is brought outside by means of a tubular duct followed by a coil, located inside the water tank; then, syngas exits through a section formed on the sidewall of the tank itself. This configuration involves excessive size of the tank that could compromise the pyrolysis itself. As pyrolysis is a slow heating in the absence of oxygen, the presence of an excessive quantity of water does cause in the reactor the presence of high water vapour mass fractions that could give origin not to pyrolysis, but to gasification or even steam reforming. To prevent this, it is necessary that the amount of evaporated water (mass fraction of H_2O) remains small. Hence, the amount of water in the tank has been reduced placing the coil outside the tank and extracting the syngas from the top of the chamber.

To overcome the above mentioned problems arising with the use of a collector, a hood has been chosen. With the hood, the output section of the syngas is placed at the top, directly on the head of the reactor over the tires. Figures 8, 9, 10 show the results of the simulations with the hood. A more uniform distribution of the pressure field (Fig. 9) and less thermal and mechanical stress of the internal elements of the chamber compared to the use of the collector are observed. The syngas flow field (Fig. 8) is concentrated around the tire, without excessive dispersions in the side areas of the chamber, index of more efficient suction. This result is also validated by the temperature (Fig. 10) that offers greater uniformity within the entire domain. Moreover, the choice of the hood obviously facilitates inserting the tire on the plate support. The depression that occurs in the chamber during the pyrolysis process has also been analyzed. Considering the autoclave closing device of the reactor, to prevent flooding of the tires, the platform of tires support has been raised by an amount calculated through Bernoulli law, also reducing the legs to a single central pivot.

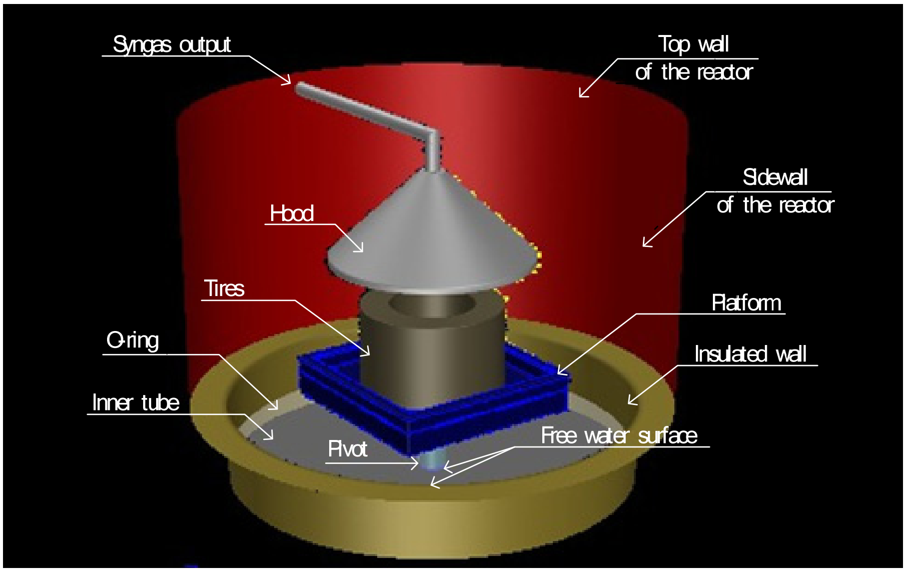

Fig. 11. A scheme of the pyrolysis reactor inner part.

According to the simulations results, the experimental plant was developed (as described in paragraph one). Figure 11 shows a diagram of the internal parts of the pyrolysis reactor built, in which the hood is present. The reactor has been also instrumented: one pressure sensor and three variable length thermocouples are placed to better acquire the temperature in the peripheral zones of the chamber and near the tire during pyrolysis.

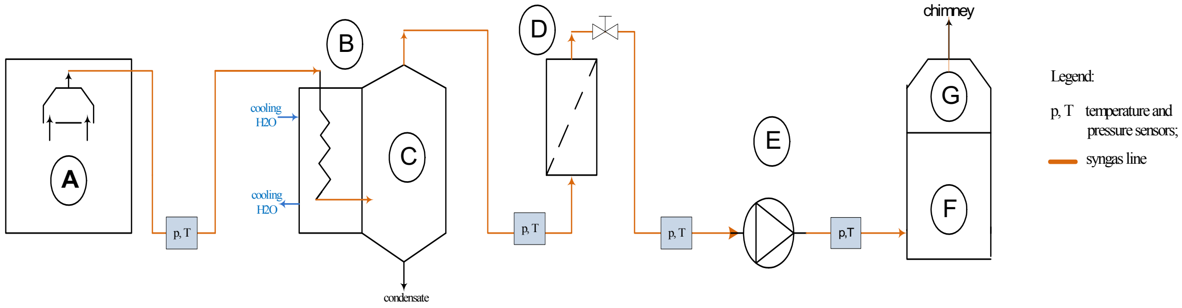

Fig. 12. Scheme of the test bench: main sensor placement.

The whole test bench has been also well instrumented to monitor and acquire data. Figure 12 shows a scheme of the syngas line, in which pressure and temperature sensors displacement are reported. Moreover, to acquire and measure the syngas speed velocity a hot-wire anemometer is placed in the duct after the output of the hood, while the molar faction of the syngas chemical species are acquired by a gas-chromatograph positioned before the burner.

4. Preliminary experimental results

In this section the experimental results obtained by whole scrap tires pyrolysis in the test bench built by CURTI SpA have been shown. Various test campaigns were conducted to investigate syngas production. To process experimental data an in-house calculating program using VBA has been developed. Introducing the data directly measured by sensors, this program calculates, at each acquisition time, the mass flow, the molecular mass, the density, and the Lower Heating Value, LHV, of syngas produced and every single chemical species in it. In addition, the program also calculates the thermal power produced. In particular, these inputs are required: chemical species molecular masses measured by the gas chromatograph, the speed of the syngas extracted from the reactor measured by the anemometer, the frequency of the fan and temperatures and pressures measured by sensors located along the gas line. Then, through an in-house developed macro, the syngas speed measured by the anemometer is corrected with instrument profile factor and the nominal diameter of the duct section, and all experimental values are reported at the same sampling frequency.

At first, pilot runs were carried out to verify the correct operation of the reactor and the whole plant. Then, tests using both new and exhausted tires were carried out.

Table 2 summarizes the results obtained using new tires. Precisely, two new tires with total weight of 13.94 kg were introduced into the reactor. The test duration was equal to 150 minutes; the laboratory temperature at the start time was equal to 18.7 °C.

Table 2. Tires pyrolysis test results.

Pyrolysis products	***Units***	**Values**
Liquid (water + oil)	*(Kg)*	15.91
H_2O	*(Kg)*	10.38
Oil	*(Kg)*	5.53
Metal	*(Kg)*	1.32
Char	*(Kg)*	4.61
Gas	*(Kg)*	2.48
Organic matter fraction transformed into oil and syngas	*(%)*	63.47

Table 3 shows the comparison between the products obtained from the pyrolysis of new tires (left) and scrap ones (right), assuming tests duration and operating temperature equal to 150 minutes and 500 °c, respectively. These results show as the syngas composition obtained from the pyrolysis strongly depends from three main factors: i) the composition of the tire, in particular the metal percentage that composes it, ii) by the use that has been made (for use in automobiles, in trucks, in tractors, ect), and especially the degree of wear.

Table 3. Pyrolysis results obtained using new tires (left) and scrap tires (right).

Pyrolysis products (NEW tires)	Values (kg/ kg tire)
Steel	0.09
Char	0.33
Oil	0.40
Gas	0.18

Pyrolysis products .. (SCRAP tires)	Values (kg/ kg tire)
Steel	0.11
Char	0.35
Oil	0.24
Gas	0.30

Table 4 shows the average composition of the syngas obtained from the tires pyrolysis, while Table 5 shows the Lower Heating Values (LHV) of the main pyrolysis products: gas, oil, char and steel. It is noted as both the syngas and the oil have high LHV, such as to be able to provide for the use as fuel in thermo-electric plants and in internal combustion engines, respectively.

Table 4. Average composition of the pyrolysis syngas.

Chemical species	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	H_2S	C_3	C_4
mass fraction [%]	11.71	24.18	6.24	8.23	7.40	9.28	0.19	6.21	18.28
m/m fraction [%]	0.70	11.50	5.18	10.73	6.15	8.27	0.19	7.93	30.39

Table 5. Lower Heating Value of the main products

Pyrolysis products	LHV[kJ/kg]
syngas	40500
oil	38000
char	32000

5. Conclusions

An experimental plant for whole scrap tires disposal by pyrolysis was designed and built at the CURTI S.p.A. laboratory. The plant is characterized by innovative and patented in-house components, in particular the pyrolysis reactor, fitted with the autoclave closing and equipped with a base acts as explosion-proof water system.

The pyrolysis reactor was developed with the help of numerical analysis in the pre-realization phase. Thanks to fluid dynamic simulations it was possible to optimize the size of the reactor, the type and the placing of both the vacuum system to extract the syngas and of the measuring sensors.

The system allows to process whole scrap tires, thus reducing their high disposal cost: introducing whole tires directly in the pyrolysis chamber without any type of pre-treatment, the plant is capable of producing separately as pyrolysis products: syngas, oil, char and metals, that can be used as energy sources for other systems.

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